II.A.1 Low Cost Hydrogen Production Platform

Tim Aaron
Praxair, Inc.
175 East Park Drive
PO Box 44
Tonawanda, NY 14151
Phone: (716) 879-2615; Fax: (716) 879-7567
E-mail: tim_aaron@praxair.com

DOE Technology Development Manager:
Arlene Anderson
Phone: (202) 586-3818; Fax: (202) 586-9811
E-mail: Arlene.Anderson@ee.doe.gov

DOE Project Officer: Jim Alkire
Phone: (303) 275-4795; Fax: (303) 275-4753
E-mail: James.Alkire@go.doe.gov

Contract Number: DE-FC36-01GO11004

Subcontractors:
Boothroyd-Dewhurst Inc., Wakefield, RI
Diversified Manufacturing Inc. Lockport, NY

Start Date: April 1, 2001
Projected End Date: September 30, 2008

Objectives

- Develop a low cost on-site hydrogen production system
  - Utilize existing technologies – steam methane reforming (SMR)
  - Have a plant capacity of 4.8 kg/h
  - Approach the DOE goal of $1.50 - $2.00/kg (production only)
  - Gas station capacity and size - single, easily installed skid
- Integrate prototype system into a fueling station
  - Design, construct and test prototype system
  - Install prototype system at the Los Angeles International Airport (LAX) hydrogen fueling station
    - Includes installation of 700 bar compression and dispensing
    - Operation of the system for 2 years

Technical Barriers

The Hydrogen, Fuel Cells and Infrastructure Technologies Multiyear Program Plan technical barriers addressed in Phases II and III of this project include:

Hydrogen Production

(A) Reformer capital costs
(B) Reformer manufacturing
(C) Operation and maintenance (O&M)

Technology Validation

(C) Lack of hydrogen refueling infrastructure performance and availability data
(D) Maintenance and training facilities
(E) Codes and standards

Technical Targets

	2006	2010	2015
Energy efficiency (LHV)	70%	72%	75%
Cost of hydrogen ($/gge)	3.00	2.50	2.00

- Life of unit: 15-20 years
- Single skid, easily-installed unit

Accomplishments (Phase II: June 2006 – May 2007)

- High temperature component
  - Prototype design complete
  - Computer modeling complete
  - Material selection complete
  - Patent application submitted
- Testing
  - Lab-scale reformer testing completed
  - Full-scale testing continues
    - Reformer thermal management proven
      - Optimization testing underway
    - Catalyst
    - Burners
    - Steam system
    - Auxiliary components
    - No significant issues found to date
- Computer models updated
  - Computational fluid dynamics (CFD) models
  - Process models
  - Heat transfer models
- Phase III proposal submitted

Introduction

SMR-based hydrogen production facilities are highly capital intensive because they are custom-designed and are built using one-at-a-time design and fabrication techniques. Capital costs account for 70-85% of the total per unit hydrogen costs for on-site systems in the 48 kg/h and below capacity range. As a result, the opportunity exists for substantial reductions in product hydrogen costs by introducing advanced design optimization technology. The focus of this project is to develop an integrated system for the turnkey production of hydrogen at 2.4–12 kg/h. The design is based on existing SMR technology and existing chemical processes and technologies to meet the design objectives. Consequently, the system baseline design consists of a steam methane reformer, pressure swing adsorption (PSA) system for hydrogen purification, natural gas compression, steam generation and all components and heat exchangers required for the production of hydrogen. The project scope also includes 700 bar hydrogen compression and integration of the prototype system into a gaseous hydrogen fueling station.

The focus of the project emphasizes packaging, system integration and an overall step change in the cost of capital required for the production of hydrogen at low volumes. Praxair is responsible for the overall system and process design as well as the overall project lead. The subcontractors, Boothroyd-Dewhurst Inc (BDI) and Diversified Manufacturing Inc. (DMI) evaluate the component and system designs from a manufacturing and overall design optimization viewpoint. Design for manufacturing and assembly (DFMA) techniques and computer models are being utilized to optimize the design during all phases of the system development.

Approach

Achieving low hydrogen costs from small SMR-based systems is possible through reducing capital cost, integrating components, and reducing the number of parts required. For conventional small plant designs, more than 75% of the cost of hydrogen is associated with capital costs. The development methodology for this program is to apply the DFMA design techniques to the component and system design from the early concept phase of design to the completion of the design effort. The reduction in the number of parts and the resulting integration and simplification of the plant layout significantly reduces the capital cost and the overall plant physical size. Praxair has defined a system that integrates the steam generation, reforming, shift reaction and all high temperature components into a single, highly-integrated component. The PSA purification system, as well as the overall skid layout and integration, have also been designed using the DFMA approach. This effort shows the potential to significantly reduce the capital cost required for a small hydrogen system and thereby greatly reduce the overall cost to produce hydrogen.

The Phase I design and economic feasibility analysis indicated that the potential exists for a significant reduction in the cost to produce hydrogen with a small on-site SMR-based system. Even though the economics of the preferred approach showed a step change in the unit cost of small on-site hydrogen production, a significant effort was required to fully understand the critical components and the overall system prior to introducing a commercially available unit. The main focus of Phase II of the project was to address and resolve concerns identified during the Phase I risk analysis. The risk mitigation was accomplished through detailed engineering/modeling and component testing. Phase II also had tasks related to detail design, tooling design and continued economic/business analysis. The primary goal of Phase II was to address all potential system issues and be ready to confidently build a Phase III prototype system that will meet the overall project goals of a safe, economical, maintainable and reliable system for the production of hydrogen for the transportation and industrial markets. Phase II of the program is nearing completion and has addressed nearly all of the system concerns.

The scope of Phase III of the project will be to design, construct and operate a full size prototype of the hydrogen production system. The prototype system will initially be operated and evaluated within the laboratory environment and subsequently will be integrated into a fueling station as part of the technical evaluation/demonstration of the technology for refueling hydrogen-fueled vehicles. The main system components that were individually developed and tested in the previous Phases of the project will be integrated into the complete prototype system. The prototype will include natural gas compression, reformer, shift reactor, water treatment, steam generation, heat exchangers, PSA purification and all other related components required for the commercial system. Phase III also has tasks related to component life and material testing using the test rigs developed in Phase II. Along with hardware and system testing, the computer process models, DFMA analysis, economic models and design documents for the commercial system will continue to be updated. Additional DFMA evaluations related to the skid packaging and auxiliary equipment will be completed in Phase III. In addition to the production unit development, Phase III also includes tasks for the evaluation and demonstration of product compression to 700 bar and integration/operation of the system at a hydrogen fueling station.

Results

The baseline design is a 2,000 scfh (4.8 kg/hr) single skid hydrogen system (see Figure 1). The overall system is designed to fit in a parking space at a typical fueling station and is designed for all domestic U.S. climate conditions. The skidded hydrogen system generates hydrogen at a pressure of 100-120 psig. The compression, storage and dispensing is not included within the skid package, but is part of the proposal for Phase III of the project.

During the past year, a significant amount of effort was centered on testing and verification of the hydrogen production system and related components. The goal of the testing was to prove and optimize the overall design from both a production and reliability standpoint. Tests included reduced scale and full scale testing of all of the critical system components.

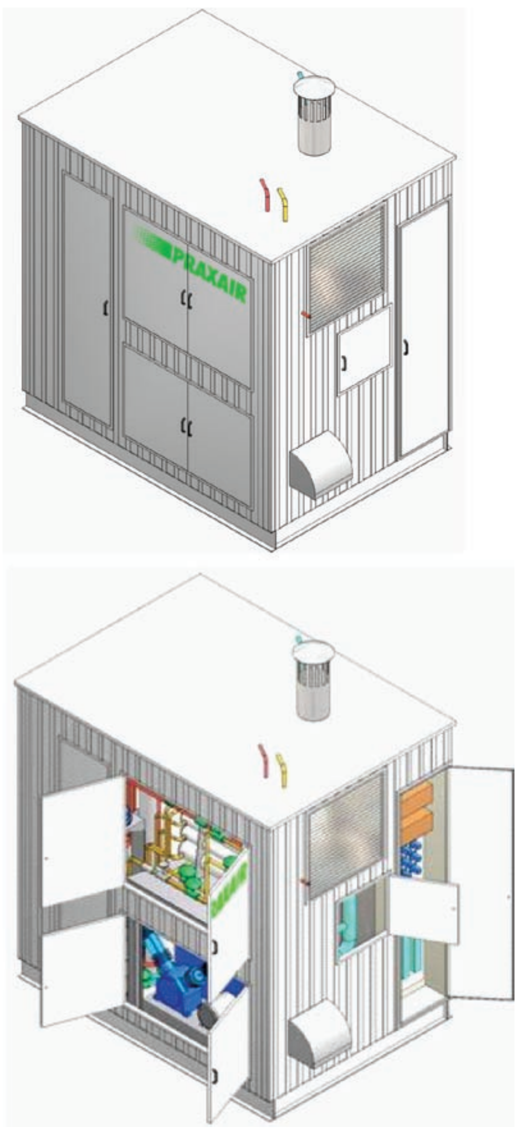

FIGURE 1. LCHPP System (Overall Skid is Approximately 7′-6″ x 10′ x 10′), Doors Closed (Top) Doors Open (Bottom)

A full-scale test rig was constructed to test all of the high-temperature components (natural gas pre-heat, desulfurization, reforming, water-gas shift reactor, steam generation and superheat, combustion, air/exhaust/process heat exchange and syngas cooling). Results to date indicate that the components and system meet the overall design goals set forth by the DOE. Testing will continue through 2007 with additional performance, optimization and materials evaluations.

The integrated high-temperature component shown in Figure 2 contains nearly all of the high temperature operations that are typically accomplished in separate components in a traditional SMR plant. By integrating all of the high temperature operations into a single component, the mass of the system is greatly reduced, the efficiency is increased and overall cost of the unit is significantly reduced. Applying the DFMA methodology to the compact integrated design has resulted in an additional cost reduction. The high level of integration does, however, present a problem for maintenance access to the individual operations. To address this concern, the critical goal of the Phase II testing was to demonstrate the reliability of these internal components to assure that the Phase III and future production systems will meet the overall reliability and maintenance goals.

FIGURE 2. Integrated High Temperature Component

Computer modeling efforts during this reporting period include the continued development of process flow and CFD models of the system design. Detailed models of the heat transfer, process stream compositions and the overall flow characteristics have been developed and verified by the component testing.

In addition to the testing, the part and assembly detail drawings of all the individual components were updated to reflect any modifications as a result of testing. No significant design modifications to the overall system have been made during this reporting period.

The system economic model has been updated continually throughout the reporting period. The cost models have been updated to reflect the latest parameters per the DOE technical plan for hydrogen production. The baseline for the cost models is now a 20 year analysis period, 10% internal rate of return (IRR) after taxes, 1.9% inflation, 70% utilization factor, 0.08/kWhr power and $5.24/MMBTU natural gas. Since the system being developed in this program is designed to produce significantly less hydrogen than the DOE baseline system, a second line (red in Figure 3) has been added to estimate the Low Cost Hydrogen Production Platform (LCHPP) system unit hydrogen cost at an increased utilization (98%). Also, if the system was scaled up to the DOE target capacity (1,500 kg/day), the expected product cost is shown using the green line.

The costs shown in Figure 3 represent a potential step change in the cost to generate hydrogen at small volumes. Typically, SMR systems 20 times larger than the 4.8 kg/h design would be required to achieve similar unit hydrogen costs. As a result, the potential exists for a cost competitive, new benchmark for on-site hydrogen generation using existing SMR and related technologies at product flow rates of 4.8 kg/h. The effect of having a cost competitive 4.8 kg/h plant is that lower volume customers have a cost effective alternative to tube trailer or liquid supplied hydrogen.

The DOE has specified 62 kg/h as the baseline for on-site gas station-sized hydrogen production which assumes that 100% of the automotive fueling will be hydrogen. Although this may be the case in the future, the ramp up to that level will likely take decades. In the interim, the 4.8 kg/h, or multiple 4.8 kg/h systems, will likely be more economical than a large 62 kg/h system operating at reduced capacity. Figure 4 compares the DOE target baseline plant size of 62 kg/h to the 4.8 kg/h system(s) at flow rates up to the DOE baseline capacity of the 62 kg/h system.

The data in Figure 4 shows that for flow rates up to 14 kg/h (700 hydrogen-powered cars supported), multiple small 4.8 kg/h systems provide the lowest overall hydrogen cost. This means as the demand for hydrogen at fueling stations increase over many years,

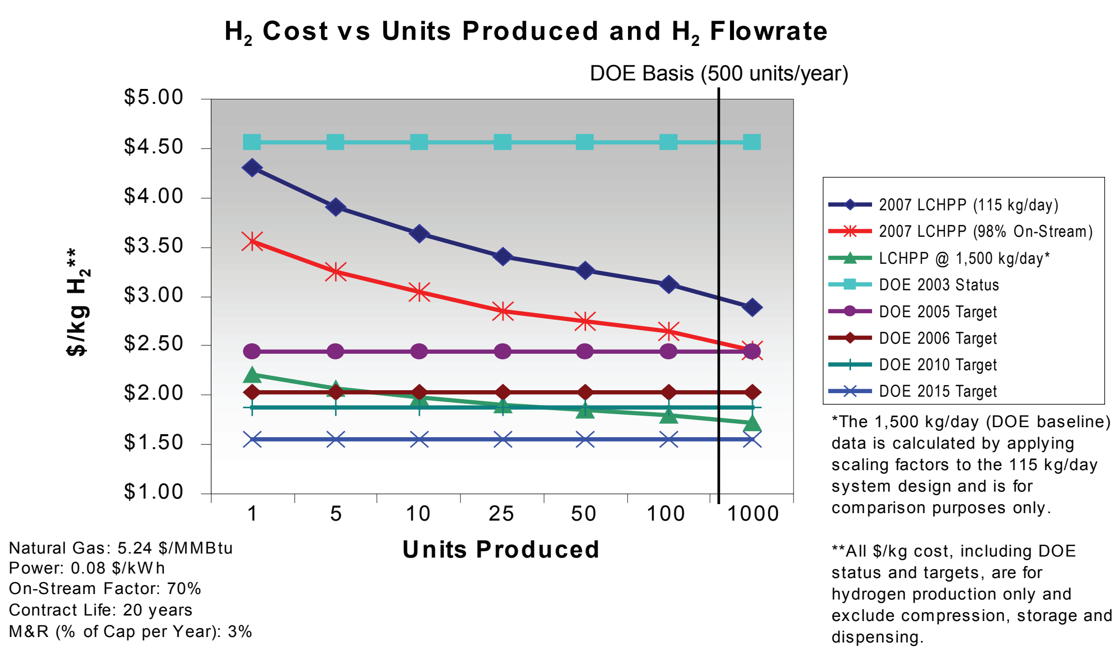

FIGURE 3. Current Estimated Cost to Produce Hydrogen from the LCHPP System

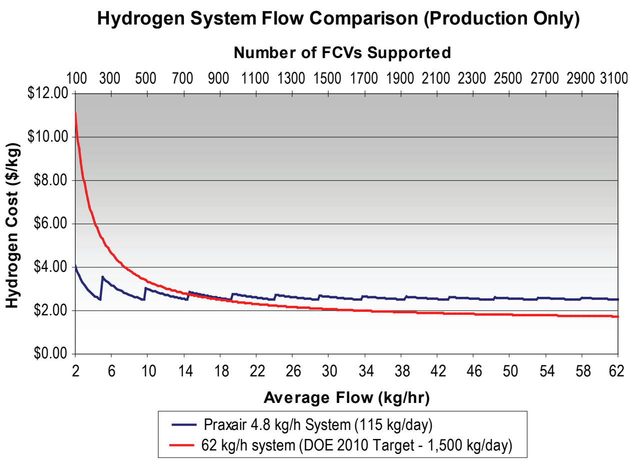

FIGURE 4. Praxair LCHPP System versus the DOE Baseline Target Capacity

additional small systems can be added to meet the demand with a high utilization of capital.

Conclusions and Future Directions

1. Applying DFMA principles to the overall design significantly lowered the cost to produce hydrogen from an SMR-based hydrogen generating system.
2. A complete hydrogen generating system producing 4.8 kg/h (2,000 scfh) can be packaged in a single skid that is small enough to easily fit into a typical parking space.
3. A new benchmark appears possible for the cost of hydrogen produced from current process technologies (i.e. SMR, and PSA purification).
4. Preliminary results will need to be verified to ensure that the system is safe, robust and meets the overall project goals.
5. The Phase II testing has shown that the components are reliable and cost effective. The next step is to assemble and operate a complete prototype unit.
6. A prototype system is planned to be installed at the LAX fueling station in 2008.
7. The Phase III scope of the project has been expanded to include high-pressure compression (700 bar) and dispensing.

FY 2007 Publications/Presentations

1. A presentation regarding the overall program status was given at the DOE Annual Merit Review Meeting (May 2007).

2. A paper and presentation was given at the 2006 International Forum on DFMA sponsored by Boothroyd-Dewhurst the week of June 19th 2006. The paper is titled DFMA Approach to Reducing the Cost of Hydrogen Produced from Natural Gas.

3. A paper and presentation will be given at the 2007 ASME conference in Seattle Washington in November. The paper is titled Development of a Cost-Effective Hydrogen Production System for Vehicle Fueling Stations.